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May 5, 2008

High Temperature Plasma Diagnostics
Albuquerque, NM, United States
May 11, 2008 through May 15, 2008

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12.6 keV Kr $K\alpha$ X-ray Source For High Energy Density Physics Experiments

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A high contrast 12.6 keV Kr $K\alpha$ source has been demonstrated on the petawatt-class Titan laser facility. The contrast ratio ($K\alpha$ to continuum) is 65, with a competitive ultra short pulse laser to x-ray conversion efficiency of 10^{-5} . Filtered shadowgraphy indicates that the Kr $K\alpha$ and $K\beta$ x-rays are emitted from a roughly 1×2 mm emission volume, making this source suitable for area backlighting and scattering. Spectral calculations indicate a typical bulk electron temperature of 50-70 eV (i.e. mean ionization state 13-16), based on the observed ratio of $K\alpha$ to $K\beta$. Kr gas jets provide a debris-free high energy $K\alpha$ source for time-resolved diagnosis of dense matter.

PACS numbers: 52.25.Os, 52.38.Ph, 52.50.Jm

Author email address: kugland@ucla.edu. Contributed paper, published as part of the Proceedings of the 17th Topical Conference on High-Temperature Plasma Diagnostics, Albuquerque, New Mexico, May 2008. Abstract program number: H18

I. INTRODUCTION

High energy density physics experiments frequently utilize x-ray probing of dense plasmas. These experiments use photons or particle beams to heat matter to solid density and higher, requiring a bright source of relatively hard x-rays ($E > 10$ keV) to adequately penetrate the plasma [1]. Two typical x-ray diagnostics are radiography [2] using an area backlighter [3] and x-ray Thomson scattering [4–6]. For both applications, it is important to develop intense, narrow bandwidth x-ray sources to yield a sufficient ratio of the scattering or transmission signal to the background (including continuum) radiation. $K\alpha$ x-ray sources are spectrally narrow and are emitted over only several ps [7] even for extended sources [8], making them well-suited for both backlighting and scattering. High dynamic range scattering data require a high contrast ratio (the ratio of the $K\alpha$ line intensity to the continuum intensity), which has been difficult to achieve in mid and higher Z $K\alpha$ sources [9].

In the work presented here, we show that Kr gas jets irradiated by ultra short laser pulses are high contrast, debris-free extended sources of $K\alpha$ x-rays at 12.6 keV with competitive conversion efficiency and narrow bandwidth. The contrast ratio is 65, a factor of 4 higher than the value previously measured for foils of similar Z [9] and the conversion efficiency (from laser energy to x-ray energy) is 2×10^{-5} , in the range previously measured [1]. Bandwidth of the $K\alpha$ line is $\Delta E/E = 2 \times 10^{-2}$, sufficient for Thomson scattering in the Compton regime [10], from a source that measures roughly 1×2 mm. We also have investigated the plasma parameters (density, tempera-

ture, and ionization state) for a fuller description of the source.

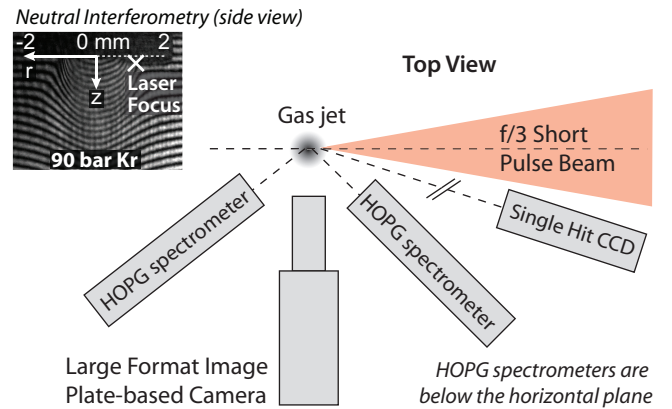


FIG. 1: (Color online) Top view of the experimental setup (the gas jet fires into the page) and neutral density interferometry (inset).

II. EXPERIMENTAL SETUP

We used the petawatt-class Titan laser facility at the Lawrence Livermore National Laboratory to produce Kr $K\alpha$ x-rays. The Titan short-pulse beam delivers a maximum of 400 J of 1054 nm light in 0.4 ps, for up to 1 petawatt of power. A long pulse beam is also available for up to 1 kJ of 1053 nm light in nanosecond-length pulses. Short pulse focusing is achieved with an f/3 off-axis parabola to a $1/e^2$ spot diameter of $15 \mu\text{m}$, giving a typical short pulse laser intensity on target above 10^{20} W/cm².

The laser was focused onto a super sonic Kr gas jet controlled by a solenoid valve that was pulsed on 10 ms before the laser pulse arrived. We focused the laser close to the gas jet nozzle and near the front edge of the gas jet ($z = 0.2$ mm and $r = 1.2$ mm, respectively, as seen in

Fig. 1) in order to maximize conversion efficiency [11]. Backing pressure was kept at 90 bars to ensure efficient laser absorption. High backing pressure causes clustering of the Kr gas into solid-density particles due to the adiabatic expansion of the gas, and clustering gas jet targets can absorb $> 95\%$ of the incident laser light [12]. A Lloyd's mirror interferometer [13] was used off line to measure the neutral density of the Kr gas jet. Abel inversion analysis indicated a neutral density of $8.7 \times 10^{19} \text{ cm}^{-3} \pm 10\%$ on axis at the nozzle exit. The gas jet nozzle was a conical super sonic nozzle with $d_{\text{exit}} = 2 \text{ mm}$, throat diameter $d_{\text{crit}} = 1 \text{ mm}$ and an expansion length of 6 mm.

A single hit counting CCD [1, 14] captured broad bandwidth time integrated x-ray spectra. This well-established technique uses a CCD camera placed far enough away from the x-ray source that a series of single photon events are recorded on the detector. Single event histogram binning [14] of the image yields an absolute number of photon events at discrete energies. In our setup, the single hit CCD observed the front side of the gas jet from approximately 5 meters away, filtered by a 0.6 mm Be vacuum window, 4 m of air, and a 0.5 mm Be filter at the CCD.

In addition, two highly oriented pyrolytic graphite (HOPG) Bragg-diffraction spectrometers recorded time integrated x-ray spectra with higher resolution in a narrower spectral region. HOPG crystals operate in the mosaic focusing mode [15, 16] for high reflectivity even at multi-keV photon energies [16, 17]. The spectrometers dispersed incoming x-rays onto image plates (Fujifilm BAS-TR) filtered with $25 \mu\text{m}$ of mylar and $25 - 150 \mu\text{m}$ of Al. Previous work with Ar gas jets [11] found that the front side of the target yields cleaner spectra, and so we placed two HOPG spectrometers to observe both the front and rear sides of the gas jet, from 45 degrees below the laser axis at a distance of 22 cm. We found no significant difference in spectral quality between the two spectrometers, presumably because they were located out of the laser-target plane. Our HOPG spectra are consistent with the single hit spectra.

In the side-on view, a large format image plate based camera was operated with a $25 \mu\text{m}$ Ta foil in place of a pinhole. The foil corner was positioned to cast both horizontal and vertical shadows on an image plate detector, in order to determine the source dimensions in the horizontal and the vertical directions. The camera body was constructed out of 7 mm thick Al with an interior shield of 1 mm teflon to attenuate any Al K-shell fluorescence due to hot electrons striking the camera body.

III. SPATIAL DISTRIBUTION OF $K\alpha$ AND SPECTRAL COMPOSITION

We measured the spatial distribution of the $K\alpha$ and $K\beta$ emission with filtered shadowgraphy from the image plate based camera. The camera was filtered with $25 \mu\text{m}$ of Pb (to block radiation below Kr $K\alpha$ and attenuate Kr $K\beta$ due the Pb L-shell edge at 12.8 keV) and $100 \mu\text{m}$ of Al (placed between the Pb filter and the image plate to block Pb fluorescence). The $25 \mu\text{m}$ thick Ta foil was

placed in the nose of the camera (instead of a pinhole), located 5.3 cm away from the center of the target chamber and 20.5 cm in front of the image plate for a magnification $M = 3.9$. As seen in Fig. 2 a), the shadow cast by the corner of the Ta foil captures the edge response g of the point source function (PSF) with the straight edges of the foil in x and y , the horizontal and vertical directions [18]. The spatial derivatives dg/dx and dg/dy are the associated line spread functions that represent one-dimensional integrated profiles of the point source function. A Gaussian point source function has Gaussian line spread functions, and so by assuming cylindrical symmetry we can use the two line spread functions to tomographically recreate the two-dimensional source projection visible in Fig. 2 b). We see an astigmatic source with FWHM dimensions of $1.7 \times 1.0 \text{ mm}$, oriented along the laser axis. Finite camera alignment accuracy introduces an uncertainty in the x and y dimension measurements of $\pm 12\%$ and $\pm 8\%$, respectively, estimated from the variation of intensities along the edge shadows. These findings are consistent with the one-dimensional source size given via source broadening on the HOPG [16]. Previous work in Ar at lower laser intensity and energy [19] found a smaller astigmatic source of x-rays above 0.5 keV, also oriented along the laser axis.

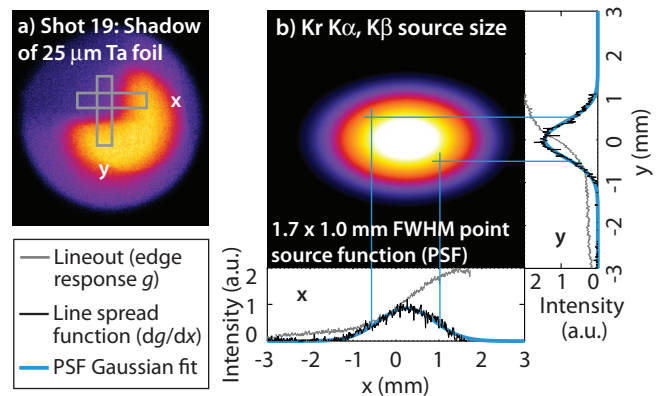


FIG. 2: (Color online) a) Filtered shadowgraph of Kr $K\alpha$ and $K\beta$ emission, b) Tomographically reconstructed x-ray source size assuming cylindrical symmetry.

The single hit spectrum shown in Fig. 3 a) shows Kr $K\alpha$ at 12.6 keV and Kr $K\beta$ at 14.1 keV with almost no background emission and an exceptionally high contrast ratio of 65. We define the contrast ratio as the ratio of the $K\alpha$ line intensity to the background intensity. At 12.6 keV, the measured bandwidth from the single hit spectrum is $\Delta E/E = 2 \times 10^{-2}$, including broadening due to the single hit CCD response. After correcting for source and depth broadening [16], the bandwidth measured from the HOPG spectra is $\Delta E/E = 5 \times 10^{-3}$. Additionally, the observed Kr $K\alpha$ line in both cases is broadened by emission from multiple ionization states. No highly ionized He-like x-ray line emission is visible, indicating a plasma bulk electron temperature below 1.9 keV, the ionization energy of the last Kr L-shell electron.

Simulations of the laser interaction using the 1-dimensional particle-in-cell code LPIC [20] predict a hot

electron distribution with a characteristic temperature of 3 MeV for laser intensities of 10^{20} W/cm², as seen in Fig. 3 (b). A hot electron fraction in the entire plasma of 0.005% at 3 MeV is consistent with the relative volumes of the directly and indirectly heated plasmas. Assuming a plasma opacity length of 1 mm (i.e. the $K\alpha$ source size in the vertical dimension as seen in Fig. 2) and an emission time of 10 ps [8] the spectral code FLYCHK [21] can be used to simulate the source-broadened spectrum shown in Fig. 3 (a) with bulk electron temperatures T_e ranging between 50 and 70 eV, depending on the shot. The bulk T_e is calculated separately based on the measured ratio of $K\alpha$ to $K\beta$ integrated line intensities from the single hit spectra, and is consistent with previous temperatures observed in Ar gas jets [11]. These temperatures indicate a Kr ionization state of 13-16; using the neutral density measurement we therefore have a plasma electron density $n_e = 1.1 - 1.4 \times 10^{21}$ cm⁻³ $\pm 10\%$. This analysis is valid during the $K\alpha$ emission phase of the plasma evolution, i.e. before the hot electrons (and any associated return current electrons) relax below the Kr K-shell ionization threshold.

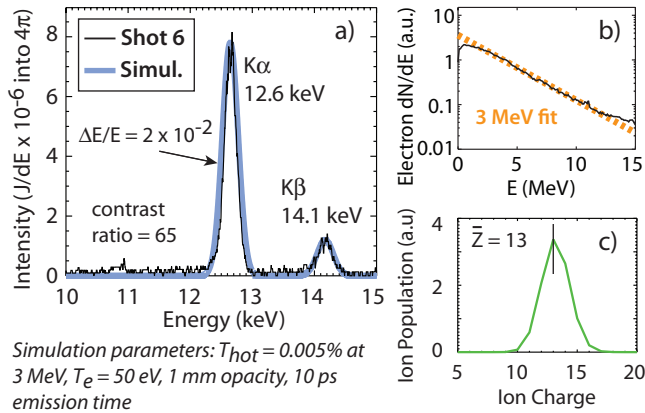


FIG. 3: (Color online) a) Time-integrated measured (single hit CCD) and simulated (FLYCHK) Kr x-ray spectra for $T_e = 50$ eV, b) LPIC simulated electron distribution, c) Kr ion charge at $T_e = 50$ eV.

IV. CONVERSION EFFICIENCY

Integration of the $K\alpha$ peak shown in Fig. 3 yields the absolutely calibrated laser to Kr $K\alpha$ x-ray conversion ef-

ficiency, which is up to 2.1×10^{-5} with corresponding yields of up to 1×10^{10} photons per joule of laser energy into 4π . This conversion efficiency is competitive with $K\alpha$ sources produced with metal foils of similar Z in previous work [1] that showed conversion efficiency in the 10^{-5} to 10^{-4} range. Measurements of conversion efficiency and photon yield from the single hit camera have a total relative error of 30% due to uncertainty in the single hit efficiency [14] at 12.6 keV. Assuming the same integrated reflectivity at 12.6 keV as what has been previously measured for 8.6 keV [16], the HOPG spectral data confirm this conversion efficiency within the experimental error bar.

V. SUMMARY

In summary, we have shown that Kr gas jets irradiated by ultra short laser pulses are high contrast, debris-free extended sources of $K\alpha$ x-rays at 12.6 keV with competitive conversion efficiency and narrow bandwidth. Such sources are suitable for area backlighting and high dynamic range scattering. Future work will investigate these applications, use time-resolved diagnostics to measure the temporal resolution available with Kr gas jet $K\alpha$ sources, and model the plasma and x-ray emission in more detail.

VI. ACKNOWLEDGMENTS

We would like to thank the staff of the Jupiter Laser Facility for their support. This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory, through the Institute for Laser Science and Applications, under contract DE-AC52-07NA27344. The authors also acknowledge support from Laboratory Directed Research and Development Grant No. 08-LW-004 and the LLNL Lawrence Scholar fellowship program.

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